The development and performance of the Minfurn carbon-regeneration furnace

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SYNOPSIS

The Minfurn is a novel carbon-regeneration furnace developed at Mintek. It combines the advantages of direct resistive heating in a vertical-tube furnace with those of continuous operation, in a furnace whose capital, operating, and maintenance costs compare favourably with those of conventional rotary kilns. After successful tests under experimental conditions on carbons containing different contaminants, a 3 kg/h unit was installed on the carbon-in-pulp (CIP) plant at the Klipwal Gold Mine near Piet Retief, where it has been operating at, on average, 123 per cent of its design capacity. Since the installation of the Minfurn, monthly average losses of dissolved gold of less than 0,02 p.p.m. have been maintained for several successive months for the first time since January 1989. It is also possible that the monthly average residue values have been reduced. Further improvements to the carbon circuit are possible, and the possibility of making further savings by a reduction in the carbon-throughput rate still needs to be investigated. The mathematical modelling of the furnace has progressed to the stage where the future scale-up and design of the Minfurn can be carried out by simulation of the performance of different designs, and choosing the design that yields the desired performance.

SAMEVATTING

Die Minfurn is 'n nuwe soort koolstofregenerasieoond wat Mintek ontwikkel het. Dit kombineer die voordele van direkteweerstandsverhitting in 'n vertikalebuisoond met dié van kontinue werking in 'n oond waarvan die kapitaal-, bedryfs- en onderhoudskoste gunstig vergelyk met dié van konvensionele draaioonde. Nadat dit onder eksperimentele toestande suksesvol getoets is met koolstofmonsters wat verskillende kontaminante bevat, is 'n 3 kg/h eenheid in die koolstof-in-pulpaanleg by die Klipwal-goudmyn naby Piet Retief geïnstalleer waar dit teen gemiddeld 123 persent van die ontwerpkapasiteit werk. Sedert die installasie van die Minfurn is daar, vir die eerste maal sedert Januarie 1989, maandelikse gemiddelde verliese van opgeloste goud van minder as 0,02 dele per miljoen vir etlike opeenvolgende maande gehandhaaf. Dit is ook moontlik dat die maandelikse gemiddelde residuwaardes verminder is. Verdere verbeteringe aan die koolstofkring is moontlik en die moontlikheid dat daar verder bespaar kan word deur die verlaging van die koolstofdeurvoertempo moet nog ondersoek word. Die wiskundige modellering van die oond het sodanig gevorder dat die toekomstige opskaling en ontwerp van die Minfurn gedoen kan word deur die simulasie van die werkverrigting van verskillende ontwerpe en die keuse van die ontwerp wat die verlangde werkverrigting sal gee.

INTRODUCTION

Granular activated carbon (GAC) is widely used for the recovery of dissolved gold from solutions and pulps. The efficiency, and hence the profitability, of such a process is very sensitive to the affinity and capacity of the GAC for dissolved gold. Owing to the cost of GAC, it is more economical to re-use spent GAC, after it has been eluted and regenerated, than to replace it with new GAC. During thermal regeneration, contaminants that can impair the adsorptive capabilities of the carbon are selectively removed from the carbon by vaporization, decomposition, pyrolysis, and gasification[1].

Since only the carbon that is lost by spillage and abrasion is replaced with new carbon, the major proportion of the carbon in an adsorption circuit is regenerated carbon, and only a very small proportion is new carbon[2]. The performance of an adsorption plant is therefore very dependent on the efficiency of the regeneration kiln.

Rotary kilns are traditionally used for carbon regeneration. This paper describes the development of a novel carbon-regeneration furnace with some unique features and advantages. Its simplicity and relatively small size mean that its capital, operating, and maintenance costs compare very favourably with those of conventional rotary kilns, while the use of direct resistive heating (DRH) facilitates the efficient use of energy and effective regeneration. Its performance under experimental conditions and under plant conditions is described, and the results obtained to date are presented.

DEVELOPMENT OF THE FURNACE

Mintek was involved in the development of the Rintoul furnace, a batch-operated vertical carbon-regeneration furnace that utilizes DRH. The use of this configuration has the following advantages.

(a) Since the heat is generated directly in the furnace charge, the furnace walls need not be made of a thermally conductive metal. Instead, refractory materials, which are more resistant to high temperatures and chemical attack than metals, can be used.

(b) The highest temperature prevails in the charge, resulting in less severe treatment of the walls and smaller heat losses. In an externally heated furnace, at least part of the furnace wall needs to be at a higher temperature than the maximum temperature required in the charge. This subjects the furnace wall to severe conditions, and increases the overall heat losses from the furnace.

(c) Because the furnace is in the vertical-tube configuration, 100 per cent of its internal volume is

utilized, making it a relatively small furnace for a given throughput, compared with horizontal rotary kilns.

A prerequisite of DRH is that the carbon must be dry enough to be free-flowing, i.e. it must contain no surface moisture. This limits the moisture content of the carbon to less than or equal to 0,43 g per gram of dry carbon (i.e. 30 per cent). Although pre-drying adds an additional unit operation, it also has the potential advantage of making the overall drying and regeneration operation more energy efficient[3]. Since the drying of the carbon to the extent that it is free-flowing involves the removal of mainly surface moisture, the drying will mostly take place in the 'constant rate' regime[4]. It can therefore be expected that a relatively short residence time in the chosen drying equipment will be sufficient.

The Rintoul furnace[5,6] was successfully commercialized in 1983. However, it had disadvantages that could mainly be attributed to the batch mode of operation. The batchwise operation partially offset its advantage of being relatively small with relatively low capital and operating costs, and needed frequent operator involvement. Furthermore, temperature-profile measurements by Mintek revealed that not all the carbon in a Rintoul furnace is subjected to the same temperature[6]. This could lead to some carbon being subjected to excessive temperatures, while some of the carbon is not effectively regenerated.

In order to overcome these disadvantages while retaining the advantages of DRH, Mintek decided to develop a continuously operated DRH furnace. This furnace is currently being commercialized under the name Minfurn. (Since the development of the Rintoul furnace, other continuously operated DRH furnaces for the manufacture and/or regeneration of activated carbon have been developed independently by other companies. However, to the authors' knowledge, no operating data on these furnaces have been published).

A schematic representation of the Minfurn concept is shown in Figure 1. The furnace consists essentially of a thermally insulated refractory sleeve, which is extended on either side by the upper and lower electrodes. An inlet for the oxidizing gas (usually steam) is provided in the lower electrode.

The GAC to be treated is dried to the extent that it is free flowing, and then loaded into the hopper. The carbon fills the furnace, the hopper, and part of the vibrating feeder below the outlet. A suitable gap exists between the lower end of the cooling section and the vibrating feeder, so that the natural angle of repose of the GAC prevents it from flowing further than this feeder. When the feeder is switched on, the carbon at the bottom of the cooling section is moved from the furnace, while the carbon in the furnace and hopper flows downward through the furnace under gravity. The carbon can be moved either continuously or intermittently.

When a potential is applied across the two power terminals, a current flows between the electrodes through the carbon, causing it to heat up, and thus the GAC eventually reaches the set regeneration temperature on its way down through the furnace.

Since the electrical resistivity of GAC decreases with increasing temperature, the electrical resistance (and therefore the ratio of electrical potential to current) between
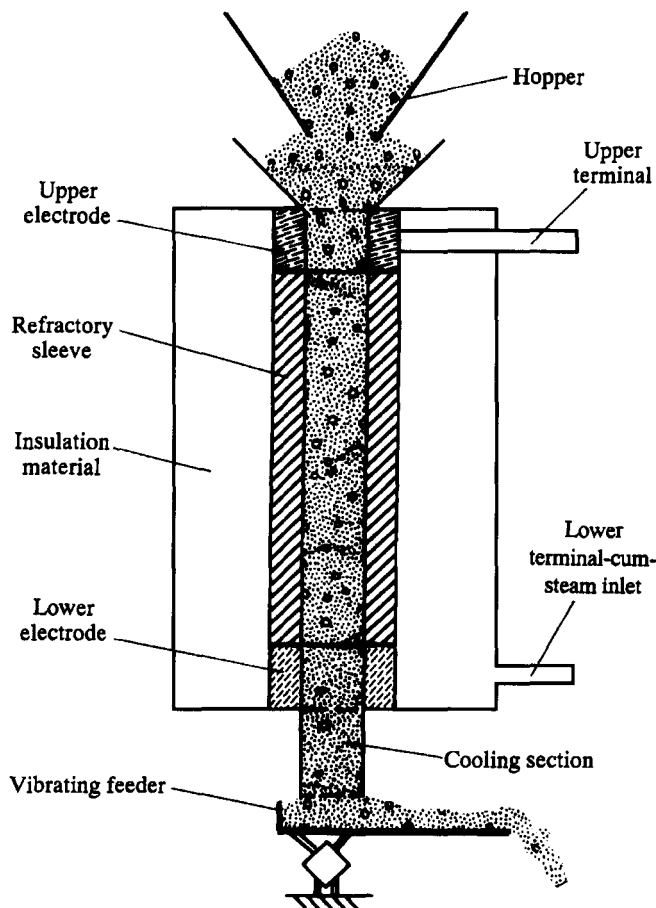

Figure 1—The basic design of the Minfurn

the two electrodes can be used as an indirect indication of the temperature profile in the furnace. If the operation of the feeder is made dependent on the electrical resistance between the electrodes, the temperature, carbon flowrate and the electrical current are regulated by one control loop.

The following automatic control strategy was chosen. A constant, predetermined electrical potential is applied across the electrodes. The vibrating feeder is normally off, leaving the carbon at rest in the furnace. As the temperature of the carbon rises, its resistance decreases, and hence the current increases. When a predetermined high current, I_1, is reached, the feeder is switched on. While the feeder remains on, hot carbon is withdrawn from the furnace, while cool carbon enters the furnace from above under gravity, thereby decreasing the mean temperature (and increasing the electrical resistance) between the electrodes. When a second predetermined current, I_2 (with $I_2 < I_1$), is reached, the feeder is switched off and the next heating cycle commences.

The use of this control strategy is unique for carbon-regeneration furnaces, and has been patented[7]. It has the following advantages.

(a) It does not rely on thermocouples, which have been found to have a limited life under the high temperatures prevailing in regeneration furnaces. (Thermocouples can be placed in the furnace for temperature measure-

ment, but the operation of the furnace is not interrupted by the failure of a thermocouple.)

(b) Unlike DRH furnaces that have manually operated/actuated valves at the outlet with which to effect the movement of carbon through the furnace, the use of a vibrating feeder, actuated by a signal from the current controller, fully automates both the temperature control and the carbon flowrate through the furnace, and probably leads to less severe handling of the carbon.

DESIGN OF THE FURNACE BY MATHEMATICAL SIMULATION

In the design of a furnace in which carbon will be subjected to the required temperature profile, and which will at the same time treat carbon at a predetermined effective throughput according to the above-mentioned control strategy, a procedure is required for the determination of the furnace dimensions and the specifications of the electrical power supply. This is not a simple relationship; for example, the electrical resistivity of GAC decreases exponentially with increasing temperature, which has the following implications:

(1) the electrical resistance between the electrodes is a strong function of the temperature profiles prevailing in the carbon bed between the electrodes, and

(2) the rate of heat generation at any position in the furnace, owing to the flow of the electrical current, is a strong function of the temperature prevailing at that position.

Furthermore, the chemical reactions and physical changes taking place in the furnace also contribute to the behaviour of the furnace. It was therefore decided to develop a mathematical model for this type of furnace. The design specifications could then be determined by the modelling of the performance of furnaces with different designs, and a design could be chosen that yields the desired performance.

An MSc study[8] was undertaken in which the following points were addressed:

(1) the development and verification of a mathematical model of a continuous DRH furnace operated at steady state, with particular reference to the specifications of carbon-regeneration furnaces used in gold-recovery circuits

(2) the determination of expressions for the physical parameters that appear in the model, based on information obtained both from the literature and during experimental work.

As a compromise between the realism of the model and the simplicity of the solution of the resulting mathematical problem, the geometry of the Minfurn shown in Figure 1 was approximated by the simplified version shown in Figure 2.

The formulation and solution of the mathematical problem are discussed in detail elsewhere[9]. The following are the most important equations that were derived and solved:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + c_1\frac{\partial T}{\partial z} + c_2 + c_3 = 0, \qquad [1]$$

where T is the absolute temperature, r and z are the radial and axial positions respectively, c_1 represents the heat transfer by convection in the furnace due to the upward
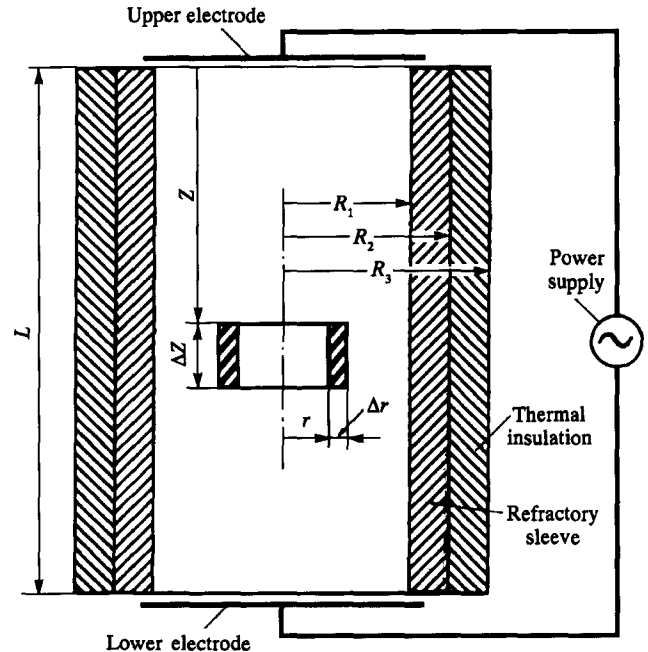

Figure 2—The model of the Minfurn

flow of gas and the downward flow of carbon through the furnace, c_2 represents the heat generated due to the electrical current, and c_3 represents the net energy consumed or liberated by the physical and chemical reactions taking place. (The kinetics of the drying and the gasification of the carbon are functions of the moisture content of the carbon and the composition of the gas phase respectively. These parameters are calculated from the solution of equations [5] and [7] respectively, as discussed below.)

Equations [2] to [4] were used as boundary conditions to equation [1]:

$$\frac{\partial T}{\partial r} = 0 \qquad \text{at } r = 0, \quad 0 \le z \le L. \qquad [2]$$

Equation [2] follows from the assumption that, at any axial position, the highest temperature prevails at the axis of the furnace.

$$\frac{\partial T}{\partial r} = -c_4\left[T - T_a\right] \qquad \text{at } r = R_1, \quad 0 \le z \le L \qquad [3]$$

Equation [3] follows from the assumption that there is only radial, and no axial, heat conduction in the refractory sleeve and insulation material. T_a is the ambient temperature and c_4 is a positive function of the furnace geometry and the resistances to thermal conduction exhibited by the GAC, sleeve, insulation material, and hypothetical stagnant air film around the outer furnace wall under natural convection conditions.

$$T = T_0 - c_5 r^2 \qquad \text{at } z = 0, \quad 0 \le r \le R_1. \qquad [4]$$

Equation [4] follows from the assumption that the radial temperature profile at the furnace inlet can be approximated by a parabolic function. T_0 is the temperature at $(r;z) = (0;0)$; c_5 is a positive function of c_4, the ambient temperature; and the temperature at the furnace inlet, c_5 is chosen so that, at $(r;z) = (R_1;0)$, both boundary conditions [3] and [4] are satisfied.

The moisture-content profile of the carbon in the furnace was calculated from

$$\frac{dq}{dz} = -c_6 \, s_{des} \, ,$$ [5]

where q is the moisture content of the carbon, s_{des} is the drying rate of the GAC, and c_6 is a positive function of the furnace geometry and the carbon flowrate.

It was found that, at the furnace inlet (i.e. at $z = 0$), the carbon descending into the furnace is pre-heated to the boiling point of water by the condensation of the saturated steam rising from the furnace. If specific heat capacities for water and carbon between 292 and 380 K of 4,2 and 0,84 kJ/(kg K) respectively are used[10,11], as well as a latent heat of vaporization of 2225 kJ/kg for water[10], it follows from an energy balance that

$$q = q_a + \left(T_0 - T_a\right)\left(0,84 + 4,2 \, q_a\right) / 2225 \text{ at } z = 0, \quad [6]$$

which was the boundary condition used in equation [5].

The composition of the gas phase was calculated from

$$\frac{d}{dz}\left(N_{CO} + N_{CO_2}\right) = -c_8 \, s_{gas} \, ,$$ [7]

where N_{CO} and N_{CO_2} are the upward molar flowrates of CO and CO_2 respectively, s_{gas} is the rate of gasification of the GAC by the steam, and c_8 is a positive function of the furnace geometry.

It is assumed that the gas phase in the furnace consists of only CO, CO_2, H_2, and H_2O. After equation [7] has been solved, the composition of the gas phase can be calculated from hydrogen and oxygen balances, as well as the theoretical equilibrium constant for the water–gas shift reaction.

The boundary condition used for equation [7] was

$$N_c = 0 \quad \text{at } z = L \, ,$$ [8]

which states that no carbon gasification products are present in the steam that is injected at the steam inlet.

This model can be used to simulate the performance of furnaces with different physical dimensions and operating with different combinations of carbon-throughput, electrical current, moisture content of the feed, etc. The specifications of the furnace (i.e. the length and inner diameter of the refractory sleeve, the thickness of the insulation, etc.), as well as the specification of the power supply (i.e. the electrical potential and power rating), can then be determined for a specific duty (the combination of carbon throughput, maximum temperature required, moisture content of feed, etc.) after identification of the combination of furnace configuration and power supply that yields the desired performance.

The validity of the model was established by comparison of the simulated and observed temperature profiles prevailing in the Minfurn under different operating conditions[8]. Examples of these results are shown in Figure 3, from which it can be seen that satisfactory predictions can be made with the model under different operating conditions.
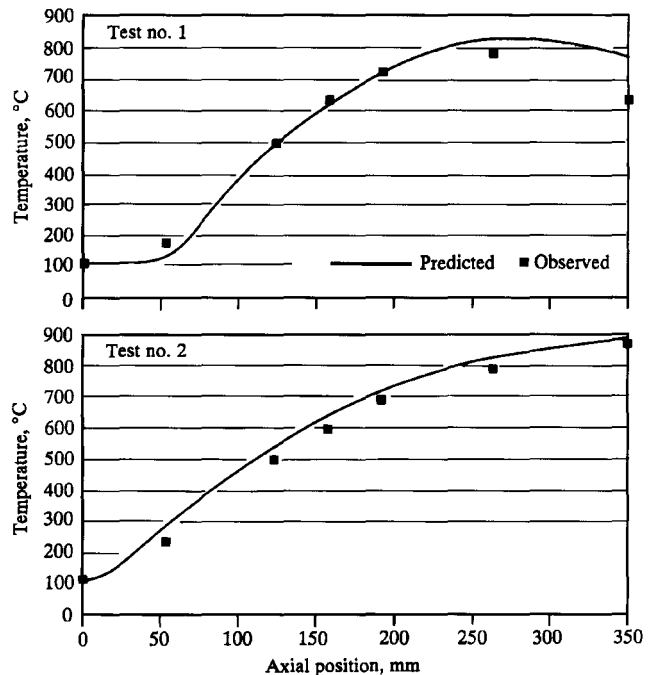
Test no.	Carbon flowrate kg/h	Steam flowrate kg/h	Moisture content g/g	Power consumption kWh/kg
1	2,3	1,1	0,12	0,57
2	3,2	0,0	0,062	0,49

Figure 3—Observed and predicted axial temperature profiles under different conditions

RESULTS DURING DEVELOPMENT AT MINTEK

Carbon Activity

The activity of carbon is defined as the amount of gold adsorbed by 1 g of carbon from 400 ml of a 20 p.p.m. gold solution in 60 minutes, expressed as a percentage of the amount of gold adsorbed by a sample of the virgin carbon under the same conditions.

Testwork

Bulk samples of eluted carbon, contaminated with compressor oil, or humic acid, and/or flotation reagents, were obtained from a number of gold plants and treated in 2-litre and 20-litre models of the Minfurn, which are capable of treating 3 and 30 kg/h of carbon respectively, in continuous campaigns. A summary of the most important results has been published elsewhere[12]. Irrespective of the nature of the contaminants, it was possible to regenerate the eluted carbon to at least 95 per cent of virgin quality, provided that a high enough temperature was maintained. The eluted carbon from one particular plant where low-activity virgin carbon is used was regenerated to an activity higher than that of the original carbon, approaching that of a high-activity virgin carbon. In these tests, it was found that a maximum temperature in the furnace of 825°C in the presence of steam is required for the effective removal of humic substances and flotation reagents.

The activity of carbon is not the only property that is important for gold recovery. When carbon is subjected to extreme temperatures during regeneration, in particular, it is important to ensure that the walls of the micropores of the

carbon are not destroyed, since this will reduce the internal surface area available for adsorption, and cause the carbon to soften. This was investigated by the treatment of both virgin and fouled carbon from another plant in repeated regeneration tests in the 2-litre furnace[12]. The carbon was subjected to a temperature profile that varied from 650°C (roughly in the middle of the furnace) to 800°C (close to the furnace outlet) for about 13 minutes during each regeneration, while about 0,1 kg of steam was introduced per kilogram of carbon. The regenerated carbon was recycled until all the carbon had been subjected to these conditions five consecutive times. These repetitive tests were carried out in order to compound any adverse effects of repeated heating, regeneration and cooling.

No deleterious effect on the equilibrium capacity for gold adsorption, the micropore and total pore volumes, or the abrasion resistance could be detected. The mass loss during regeneration of the used carbon decreased steadily from 1,4 per cent during the first cycle to 0,6 per cent during the fifth cycle. This mass loss was attributed mainly to the incremental thermal decomposition of contaminants during each cycle.

About 1,5 per cent of the mass of the virgin carbon was lost during each of the five regeneration cycles. Since the virgin carbon was not preconditioned to remove sharp edges prior to these tests, and since a reduction in the mean particle size of the virgin carbon particles was detected, it was concluded that this mass loss was largely due to attrition in the furnace. (The abrasion resistance of the unconditioned virgin carbon was about 5 per cent lower than that of the used carbon.)

RESULTS OBTAINED AT KLIPWAL GOLD MINE

The Klipwal metallurgical plant was commissioned in December 1980. A simplified flowsheet of the operation is shown in Figure 4. The plant treats about 5 kt of ore per month. Because the ore contains a fairly high proportion of free gold, it is passed through a Johnson concentrator after being milled in a 10 by 8 ft ball mill. The concentrate is passed over a James table, and the final concentrate is amalgamated. The concentrator tailings and pulp discharged from the Johnson concentrator are combined and classified with the use of cyclones. The underflow is returned to the mill and the overflow is thickened.
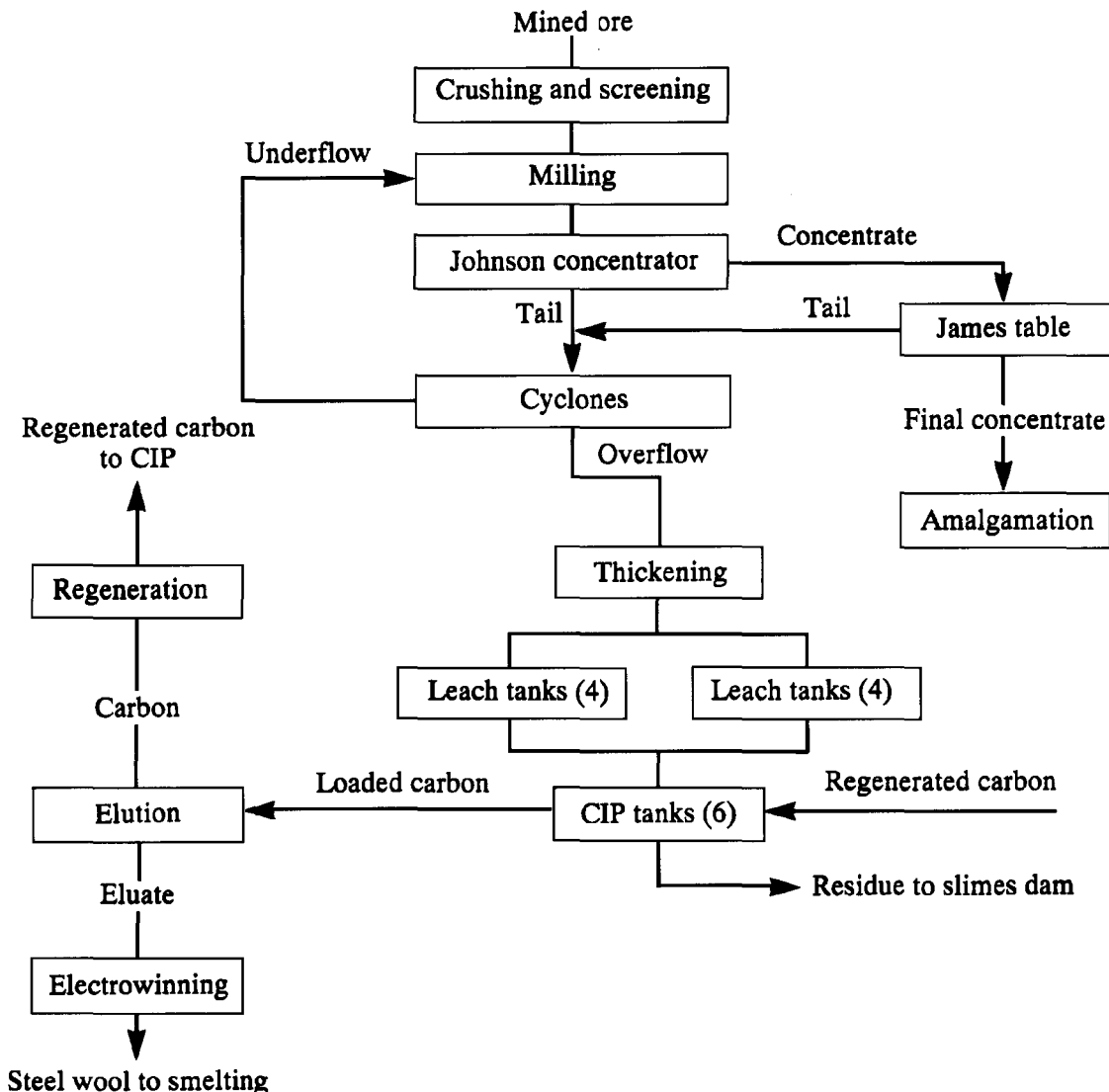

Figure 4— Simplified flowsheet of the metallurgical plant at the Klipwal Gold Mine

The thickener underflow is leached in two banks of four tanks each, operated in parallel. (These tanks are both air-agitated and mechanically agitated.) The dissolved gold is adsorbed in six carbon-in-pulp (CIP) tanks. The carbon inventory is maintained at about 19,8 g/l in the first tank and at about 18,0 g/l in the other tanks. Once a day, loaded carbon is removed from the first tank, given a cold acid wash, and eluted. The carbon in the rest of the circuit is pumped counter to the pulp flow and regenerated carbon is introduced into the last tank.

Initially, a gas-fired rotary kiln was used to regenerate the carbon. However, temperature control was difficult, resulting in damage to the brickwork of the furnace and frequent ashing of the carbon. The kiln was then sold, and the plant operated without any carbon-regeneration facility until November 1990, i.e. for almost 7 years. During this period, only enough fresh carbon to replace losses was occasionally added to the circuit.

History of the Plant Operation

The variations in the monthly average gold head and residue values between September 1986 and March 1992, and the gold value of the solution phase leaving the plant (referred to as dissolved loss), are summarized in Figure 5. The months during which notable changes were made on the plant are indicated. The three-monthly centred moving averages are also shown.

Although the gold head value fluctuated continuously, no overall upward or downward trend away from the average of 2,9 g/t was noted. The fluctuations in the residue values were always much smaller in magnitude than those in the head values. The trends observed in the gold head values can therefore be interpreted directly as trends in the amount of dissolved gold that was available for adsorption. The monthly average head values were mostly between 2,5 and 3,5 g/t and, by subtraction of the average residue value of 0,5 g/t, it was inferred that the monthly average amount of dissolved gold varied mostly between 2,0 and 3,0 p.p.m.

Between September 1986 (event 1) and January 1989, the fluctuations in the dissolved losses mostly followed the fluctuations in the gold head values. In January 1989 a compressor that supplied air to the leaching tanks was installed (event 2). In the months following that, very high dissolved-loss values were frequently noted; for example, an average dissolved loss of 0,047 g/t was recorded for August 1989. This was ascribed to compressor oil leaking into the circuit and contaminating the carbon.

The entire carbon inventory of the adsorption circuit was replaced with fresh carbon in August 1989 (event 3). The dissolved losses dropped immediately, despite a slight increase in the gold head value. However, between November 1989 and November 1990, the dissolved losses again increased steeply, despite fairly constant gold head values.

In November 1990 (event 4), a primitive regeneration furnace was improvised by the plant staff. It consisted of a drum, 1200 mm long and 500 mm in diameter, with an opening of 100 mm in diameter at one end. Thermocouples were fitted to the front and back ends so that the temperatures inside the drum could be monitored. The drum was loaded with carbon containing about 0,18 g/g (i.e. 15 per cent) moisture to about 50 mm from the top. The carbon was then heated over a coal fire until a carbon temperature
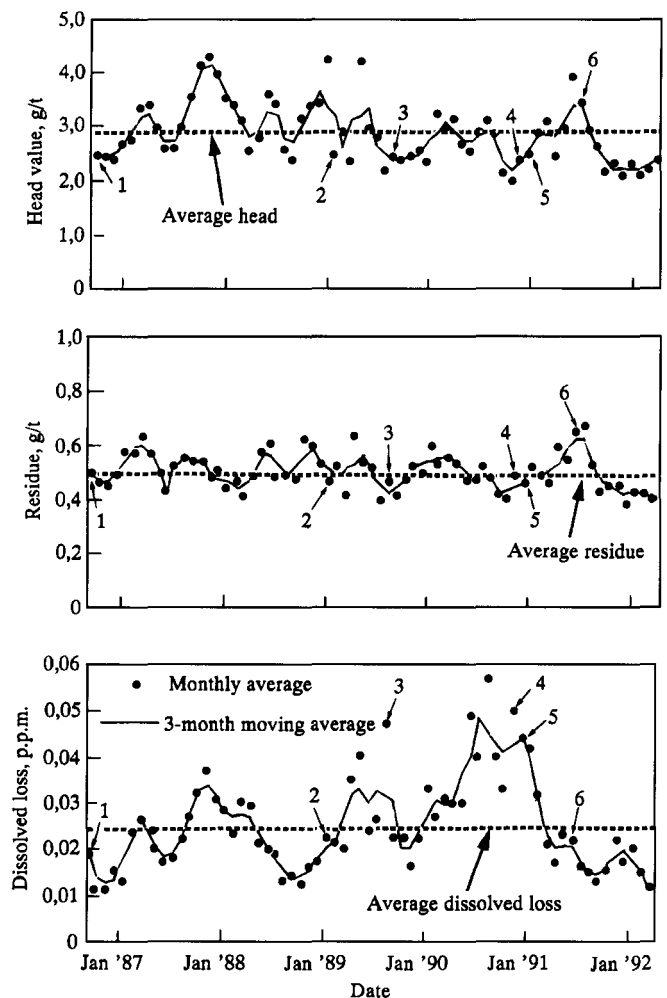
Event no.	Date	Description
1	Sep '86	No carbon regeneration used
2	Jan '89	Compressor installed
3	Aug '89	Carbon inventory replaced
4	Nov '90	Improvised furnace commissioned
5	Dec '90	Blower commissioned
6	Jun '91	Minfurn commissioned

Figure 5—Trends in the gold head value, residue value, and dissolved losses at the Klipwal Gold Mine

of about 680°C was achieved. The narrow opening through which loading and unloading took place allowed moisture and gases to leave the furnace while keeping oxygen out.

However, an even temperature could not be obtained throughout the carbon load. The reinforced bottom of the drum also burnt through regularly, necessitating frequent repairs. Furthermore, the manual loading, heating, cooling, and unloading of the furnace was very time-consuming.

Despite these difficulties, the commissioning of this furnace in November 1990, combined with the replacement of the compressor with a blower in December 1990 (event 5), led to a sharp decrease in the average dissolved losses between this time and June 1991, despite an upward trend in the gold head values. During this period, 2100 kg of carbon was treated. The adsorptive capabilities of carbon samples from the plant, taken before and after regeneration, were tested at Mintek. It was found that, with the use of the

improvised furnace, the activity of the carbon improved from 7 to 68 per cent of that of the virgin carbon used.

The development of the Minfurn was brought to the attention of the Klipwal staff. A sample of about 100 kg of fouled carbon was delivered to Mintek and regenerated in a 3 kg/h model of the Minfurn under various operating conditions. It was found that subjecting the carbon to a maximum temperature of between 620 and 720°C was sufficient to restore the activity of the carbon to that of virgin carbon.

Results* Obtained on the Plant

Based on the satisfactory regeneration results obtained at Mintek, the Klipwal management decided to purchase a 3 kg/h model of the Minfurn furnace, which was installed on the plant in June 1991. It was initially intended to sun-dry the eluted carbon to between 0,25 and 0,43 g/g (i.e. between 20 and 30 per cent) moisture. However, it was decided eventually to dry the carbon in batches in an open pan over a log fire, at least during the cooler months. The extent of drying depends on the judgement of the operator. In order to allow at least some form of control, it was decided that the carbon should be dried to the extent that no surface moisture would be visible, but the carbon should still be 'sweating'. (This is evident from the fact that it sticks to the hand when the bed is pressed upon.) This is obviously a very subjective way of control, and substantial fluctuations can be expected.

Following the commissioning of this new furnace, the dissolved losses were reduced to below the already acceptable values achieved by use of the improvised furnace. The losses were kept at between 0,012 and 0,022 p.p.m., with an average of 0,016 p.p.m. These low dissolved losses were associated with low head values between June 1991 and January 1992. However, a strong downward trend in the dissolved losses was still evident up to March 1992, although the average head values had increased again from January 1992. It can be seen from Figure 5 that, after the installation of the compressor in January 1989, monthly average dissolved losses of less than 0,02 p.p.m. were occasionally achieved, but were never maintained for more than one month. However, from the installation of the Minfurn in June 1991 until March 1992, a dissolved loss of more than 0,02 p.p.m. was observed in only one month, November 1991 (0,022 p.p.m.).

Furthermore, whereas the monthly average residue values had varied fairly consistently around 0,51 g/t, they have remained consistently below that since August 1991, at an average value of 0,45 g/t. The residue values were still following a downward trend at the end of March 1992, although the head values had been increasing since January 1992. Although the number of data points available is not yet large enough to be statistically significant, there could

possibly be a real reduction in the residue value due to the high-quality regenerated carbon competing more successfully with a mildly 'preg-robbing' constituent in the ore. Alternatively, a reduction in the residue value could result from the larger driving force (i.e. the dissolved-gold concentration gradient) for the mass transfer of dissolved gold from the solid to the solution phase, brought about by the lower gold concentration being maintained in solution.

By the end of March 1992, 19 283 kg of carbon had been regenerated in the Minfurn at an average throughput rate of 81 kg per day, i.e. 3,4 kg per hour. This represented 50 per cent of the total carbon throughput on the plant.

Between June and September 1991, log sheets and daily composite carbon samples from the mine were regularly submitted to Mintek for study and analysis. The results obtained are summarized in Figures 6 to 8. From Figure 6, it can be seen that the rate of carbon treatment fluctuated considerably during the first six weeks, and was mostly above the design capacity of 3 kg/h. The fluctuations were due to the choice of current setpoints that were too low, as well as to the overheating of the carbon during pre-drying.

The moisture content of the carbon fed to the furnace was not monitored on a daily basis. The only indications of moisture content available are the total masses of carbon fed to, and obtained from, the furnace during a week. The difference in mass can be assumed to be mostly moisture, since the mass lost due to the decomposition of the carbon and to the volatilization of impurities can be expected to be only a few per cent. Figure 7 shows the weekly average moisture content calculated from the mass losses during regeneration. It can be seen that, between 17 June and 2 September, the moisture content steadily increased from about 0,11 g/g (10 per cent) to around 0,33 g/g (25 per cent). However, the weekly fluctuations remained large and it is suspected that the daily moisture content might have fluctuated even more.

Since 20 July, the rate of carbon treatment has been maintained close to an average of 3,7 kg/h, which is equal to 123 per cent of the design capacity of the furnace. Furthermore, the moisture content of the carbon fed to the furnace was maintained at more than 20 per cent to avoid overheating of the carbon during pre-drying.

The axial temperature profile in the furnace under two different sets of conditions was simulated by means of the mathematical model discussed earlier and is shown in
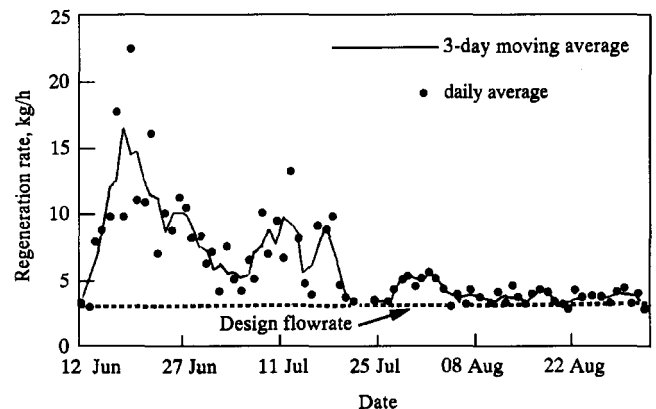
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* The activity results quoted in this section were obtained from the whole-carbon samples for the activity tests. The mean particle diameters of the regenerated- and virgin-carbon samples used for comparison in these tests were 2,24 and 2,48 mm respectively. This led to moderately optimistic activity results for the regenerated carbons, compared with what would have been obtained if only certain size fractions of the virgin- and regenerated-carbon samples had been taken for the comparisons. However, these results can still be used for relative indications of the quality of different used-carbon samples.
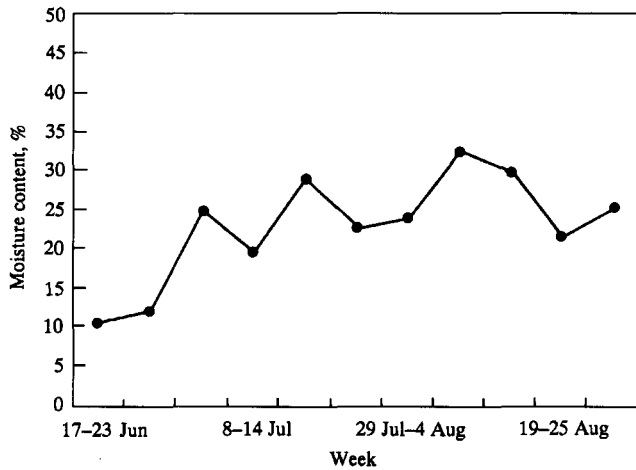

Figure 6—The daily average regeneration rate maintained at the Klipwal Gold Mine

Figure 7—The weekly average moisture content of the carbon fed to the Minfurn at the Klipwal Gold Mine

Figure 9—Simulated temperature profiles illustrating the effect of different operating conditions

Figure 9. The conditions chosen for simulation no. 1 correspond to a typical set of conditions that might have prevailed during the period up to 20 July. Under these conditions, a maximum temperature of about 600°C is reached, which is slightly lower than the minimum temperature required for restoring the activity of the carbon (620°C), as discussed earlier. The conditions chosen for simulation no. 2 correspond to the average conditions that were maintained from the middle of August, under which the carbon was maintained at more than 500°C for about 55 per cent of the total residence time in the furnace (i.e. for about 9 minutes) and a maximum temperature of about 850°C was reached, which corresponds closely to the conditions required for the restoration of the adsorptive quality of the carbon.

The activity values of the daily composite samples of regenerated carbon are shown in Figure 8. In order to make the trends clearer, the three-day centred moving averages are also shown. Although a good deal of fluctuation is evident in these results, the activities varied mostly between 80 and 120 per cent of that of virgin carbon, and were almost always better than the 68 per cent of virgin activity obtained with the use of the improvised furnace. These fluctuations can be ascribed partly to fluctuations in the moisture content of the carbon fed to the furnace, which would have caused the temperature profile in the furnace to vary accordingly, as well as to the fact that the furnace was
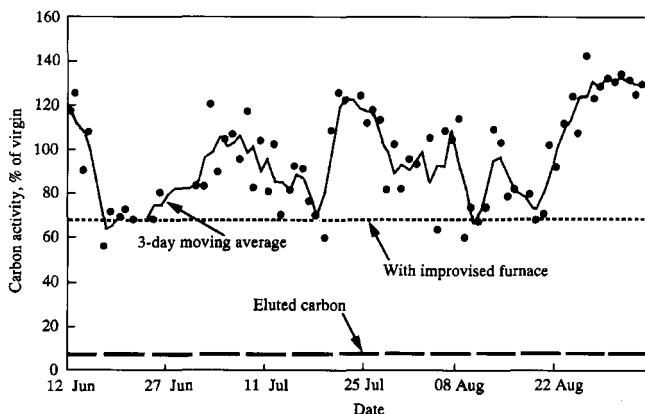
operated beyond its designed capacity. However, the activity values seem to have stabilized towards the end of the period in which the data were accumulated, by which time the moisture content in the furnace feed and the rate of carbon treatment were under control.

These activity results mostly confirm the conclusions drawn from the temperature-profile simulations discussed earlier, and serve to confirm further the validity of the mathematical model.

Furthermore, certain problems had been experienced with the elution equipment, and the ideal elution temperature was often not attained. However, the efficiency of the elution was not monitored during this project, and the possible influence of this factor on the quality of the regenerated carbon was not investigated.

Comparison of Operating and Maintenance Costs

The carbon slurry fed to rotary kilns typically contains 1 g/g (50 per cent) moisture, whereas carbon that is fed to the Minfurn has to be pre-dried to typically 0,25 g/g (20 per cent), or 0,43 g/g (30 per cent) moisture at most. Since the volatilization of moisture comprises a significant proportion of the energy input of a regeneration furnace, any comparisons of energy consumption must be based on a common initial moisture content.

For this comparison, an initial moisture content of 1 g/g (50 per cent) is used. As discussed above, the energy consumption of the Minfurn was 0,5 kWh per kilogram of carbon with an initial moisture content of 0,25 g/g (20 per cent). In order to determine the energy requirement for the regeneration of carbon with an initial moisture content of 1 g/g (50 per cent) moisture, it is necessary to estimate the energy required for pre-drying from 1 g/g (50 per cent) to 0,25 g/g (20 per cent) moisture. This total energy requirement can then be compared with results published for rotary kilns treating carbon with an initial moisture content of 1 g/g (50 per cent) moisture.

The energy requirement for pre-drying carbon containing 1 g/g (50 per cent) moisture to 0,25 g/g (20 per cent) moisture is estimated as follows.

From the literature[10,11], the following are obtained:

$$Cp_c = 0,9 \text{ kJ/kg.°C} \qquad [9]$$

$$Cp_w = 4,2 \text{ kJ/kg.°C} \qquad [10]$$

Figure 8—The daily carbon activities at the Klipwal Gold Mine

$$\lambda = 2257 \text{ kJ/kg},\qquad [11]$$

where Cp_c is the specific heat of activated carbon, Cp_w is the specific heat of water, and λ is the heat of vaporization of water.

If an efficiency of 80 per cent is assumed, the energy E required to heat 1 g of carbon and 1 g of moisture from 25 to 100°C, and then vaporize 0,75 g of the moisture, is:

$$E = [(100 - 25)Cp_c + (100 - 25)Cp_w + 0{,}75\lambda]$$
$$/\,(0{,}8 \times 3600)$$
$$= 0{,}7 \text{ kWh}.\qquad [12]$$

It has been shown that, if some of the free surface moisture is blown from the carbon with air prior to pre-drying, the initial moisture content can be reduced to about 0,54 g/g (35 per cent) moisture[3], thus allowing for pre-drying at less than 0,6 kWh per kilogram of dry carbon. However, for a more conservative estimate, the value calculated from equation [12] is used, which yields a total energy requirement of $(0{,}5 + 0{,}7) = 1{,}2$ kWh per kilogram of dry regenerated product. This compares favourably with energy consumptions of between 1,5 and 2,0 kWh per kilogram of carbon observed for an electrically heated rotary kiln fed with carbon containing 1 g/g (50 per cent) moisture[5]. It compares even more favourably with the heat requirement of 0,24 kg of liquid petroleum gas (LPG) per kilogram of carbon quoted for a gas-fired kiln[13]. At a calorific value of 50 000 kJ per kilogram, energy of 3,3 kWh is required per kilogram of carbon. (The moisture content of the carbon feed to this kiln was not reported. However, it can probably be assumed to be close to the typical value of 1 g/g.)

Until the end of March 1992, the only maintenance required on the furnace involved the replacement of the thermocouple (which is not essential for the operation of the furnace), the lower graphite electrode, and the insulators for the electrical terminals, at a total cost of about R250. The lower electrode had to be replaced as a result of the severe corrosion of the graphite around the steam inlet. The corrosion was attributed to air leaking into the furnace through the open steam inlet (no steam is used for regeneration) and oxidizing the graphite. It was subsequently decided to keep the steam inlet closed, which should prevent a recurrence of this damage.

It is conservatively estimated that two days could have been lost for maintenance, which means that the availability of the furnace was 99 per cent. If the figure of R250 is doubled to allow for maintenance labour and multiplied by 1,33 to annualize it, a combined annual maintenance supplies and labour cost of R667 is obtained, which is less than 2 per cent of the current installed list price of the unit. This figure compares very favourably with the rough estimate of the cost of annual maintenance supplies and labour given in the literature[13], namely between 10 and 15 per cent of the installed cost.

SUMMARY

The Minfurn carbon-regeneration furnace combines the advantages of direct resistive heating in a vertical-tube furnace with those of continuous operation. The furnace was tested extensively under experimental conditions on carbons from several plants, with each carbon containing different contaminants. Each carbon was restored virtually to virgin quality under the appropriate conditions. No deleterious effects on these carbons could be observed even after repeated regeneration cycles.

A mathematical model of the Minfurn was developed to the stage where it can be used with confidence to predict the conditions prevailing in Minfurn furnaces of different designs and operating under different sets of conditions. The model will play a crucial part in the scale-up of the Minfurn and in the design of customized units.

Some of the advantages of the Minfurn are its simplicity and relatively small size, which allow its capital and operating costs to compare very favourably with those of conventional rotary kilns, even if extra pre-drying equipment is needed. These advantages led to the installation of a 3 kg/h unit, with an active internal volume of about 2 litres, on the CIP plant of the Klipwal Gold Mine near Piet Retief, where 5 kt of ore is treated per month. This unit has been coping with 50 per cent of the total carbon throughput of this mine.

At Klipwal, the carbon was pre-dried to contain between 0,11 and 0,33 g/g (between 10 and 25 per cent) moisture before regeneration. Only one operator was needed to dry the carbon and to supervise the furnace. The power consumption for carbon containing an average of 0,25 g/g (20 per cent) moisture was about 0,5 kWh per kilogram of regenerated carbon obtained. It is estimated that the combined processes of drying and regeneration can be achieved with a total energy consumption of about 1,2 kWh per kilogram of carbon, which compares favourably with the total energy consumptions of conventional rotary kilns. The availability of the furnace was at least 99 per cent. The results obtained to date indicate that the total cost of maintenance supplies and labour between June 1991 and March 1992 was less than 2 per cent of the installed price of the Minfurn.

The activities of the regenerated carbon produced at Klipwal varied between 80 and 120 per cent of that of virgin activated carbon. These variations are considered to be moderate in view of the other variations, such as the moisture content of the carbon fed to the furnace, the fact that the furnace was operating at about 123 per cent of its design capacity, and the possible effects that variations in elution efficiency might have had on the adsorptive ability of the carbon.

From September 1986, the monthly average gold dissolution from the ore has generally been between 2,0 and 3,0 p.p.m. The dissolved losses after CIP have fluctuated considerably, with monthly average dissolved losses of more than 0,04 p.p.m. occasionally being observed. The temporary use of an improvised furnace reduced these dissolved losses considerably, but its operation and maintenance were labour-intensive. Since the installation of the Minfurn in June 1991, the monthly average dissolved-gold losses up to March 1992 have been maintained at between 0,012 and 0,022 p.p.m., the average being 0,016 p.p.m. Although monthly average dissolved losses of less than 0,02 p.p.m. have been achieved occasionally since January 1989, when fouling of the carbon with oil first occurred, these low levels have been maintained for several successive months only since the installation of the Minfurn. The data available to date suggest that a reduction in the

monthly average residue value of about 0,06 g/t might also have occurred since the installation of the furnace.

The difficulty of achieving an acceptably high elution temperature on the Klipwal plant is currently being addressed by the installation of a boiler. This boiler will also make it possible to introduce steam into the furnace during regeneration, whereas regeneration is currently being carried out without steam. These improvements will probably lead to a further decrease in the dissolved-gold losses.

The extent to which the present carbon-throughput rate can now be reduced while acceptable dissolved-gold losses occur will have to be investigated. This will allow the overall savings attributable to the installation of the Minfurn regeneration furnace to be maximized.

ACKNOWLEDGEMENTS

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*Double record for Sasol Coal**

Brandspruit Colliery—a mine in the Sasol Coal Mining Group—has worked one million fatality-free manshifts as well as 1000 fatality-free production shifts. The Mine, with a staff complement of 1878, worked 530 days to complete the million shifts. It is the second time that it has achieved this, having also managed it in 1988. The present records were achieved on 18th February of this year.

The prestige NOSA five-star safety status was awarded to Brandspruit for the first time in 1990, after which it was retained by the Mine on two occasions.

Since then Brandspruit has received various awards, and various achievements have been reached. These include working a million accident-free manhours on seven occasions since 1990. In 1992 an award of honour and one for merit was received from NOSA for improvement.

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In 1992 Brandspruit received an award in the gold class from the National Productivity Institute for the improvement of production.

It triumphed again in the same year when it won the award for the best programme of preventative maintenance in South Africa in a competition organized by the CSIR in conjunction with *Engineering News*.

Jannie van der Westhuizen, General Manager of the Brandspruit Mine, sums it up: 'We continually regard safety and improvement management as among the most important ways to increase competitive benefits. Good safety standards always go hand in hand with good financial results, as Brandspruit is proving. It assists us in creating a firm foundation for ongoing improvement, which is our biggest challenge, and we already have the people to lead us to new heights in the near future.'